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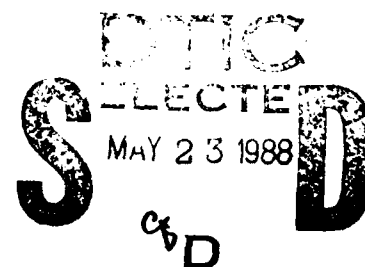
Environmental Monitoring of a Titan 34D 5¼ Segment Solid Rocket Motor Static Firing

March 1988

Authors:
G. W. Rinehart, Lt, USAF
D. D. Berlinrut, Capt, USAF

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**Air Force
Astronautics
Laboratory**

Air Force Space Technology Center
Space Division, Air Force Systems Command
Edwards Air Force Base,
California 93523-5000

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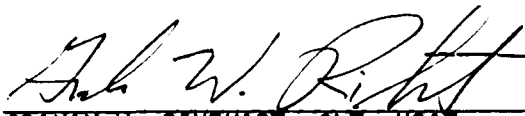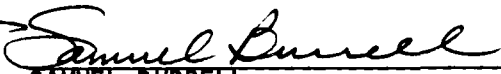
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FOREWORD
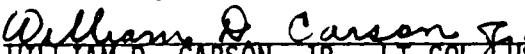
This final report documents the planning and results of the environmental monitoring of a Titan 34D solid rocket motor static firing at the Air Force Astronautics Laboratory (AFAL), Edwards Air Force Base, CA. AFAL Project Manager was Graham Rinehart.

This report has been reviewed and is approved for release and distribution in accordance with the distribution statement on the cover and on the DD Form 1473.

GRAHAM W. RINEHART, 2LT, USAF
Project Manager

SAMUEL BURRELL
Chief, Safety and Health Office

FOR THE COMMANDER

WILLIAM D. CARSON, JR., LT COL, USAF
Chief, Technical Services Division

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)
On 15 June 1987 a full-scale 5½ segment Titan 34D solid rocket motor was static fired at the Air Force Astronautics Laboratory, Edwards AFB, CA. An environmental monitoring program was initiated to assure protection of test personnel and compliance with environmental restrictions. A protocol for monitoring densely populated closed environments was developed and initiated in the Control Center. Realtime monitoring of gaseous hydrogen chloride and analysis of preserved collections of hydrochloric acid depositions was performed. Revolatilization chamber experiments were performed to predict and study the strength of acidic off-gassing. Results of the program indicate that the personnel and equipment involved in the test were adequately protected and no significant environmental impact occurred as a result of the motor firing.

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INTRODUCTION

On 15 June 1987, a 5 ½ segment Titan 34D solid rocket motor (SRM) was successfully test-fired at the Air Force Astronatucs Laboratory (AFAL) as part of the Titan Recovery Program. The two-minute firing was the first time a Titan 34D SRM was static-fired in a nozzle-down configuration.

The AFAL Bioenvironmental Engineering Office, along with Space Division's Bioastronautical Engineering Office, developed a strategy for the environmental monitoring of the Titan firing involving extensive test area and downrange monitoring. The effort involved monitoring the environment inside the Control Center to protect personnel and equipment, sampling for ground-level hydrogen chloride (HCl) downrange of the firing to document the amount of toxic gas at the base boundary, collection of acidic rainout from the exhaust cloud, and photographic tracking of the exhaust cloud to document its path across the East Range of Edwards AFB.

The firing provided an opportunity to test an experimental sampling device developed by The Aerospace Corporation, and another monitor built by Lawrence Livermore National Laboratory (LLNL) for the Air Force Engineering and Services Center (AFESC). Additional expertise in sampling and sampling equipment was provided by the Air Force Occupational and Environmental Health Laboratory (OEHL).

BACKGROUND AND OBJECTIVES

Following the in-flight failure of a Titan 34D launch vehicle in April 1986, Air Force Systems Command Space Division initiated the Titan Recovery Program. Part of the program was the evaluation of solid rocket motor segments; it was decided to test the segments at the AFAL. The High Thrust Space Booster Complex, Experimental Area 1-125, was chosen as the test site; it is located at the north end of Leuhman Ridge and is 900 feet above the desert floor (Figure 1).
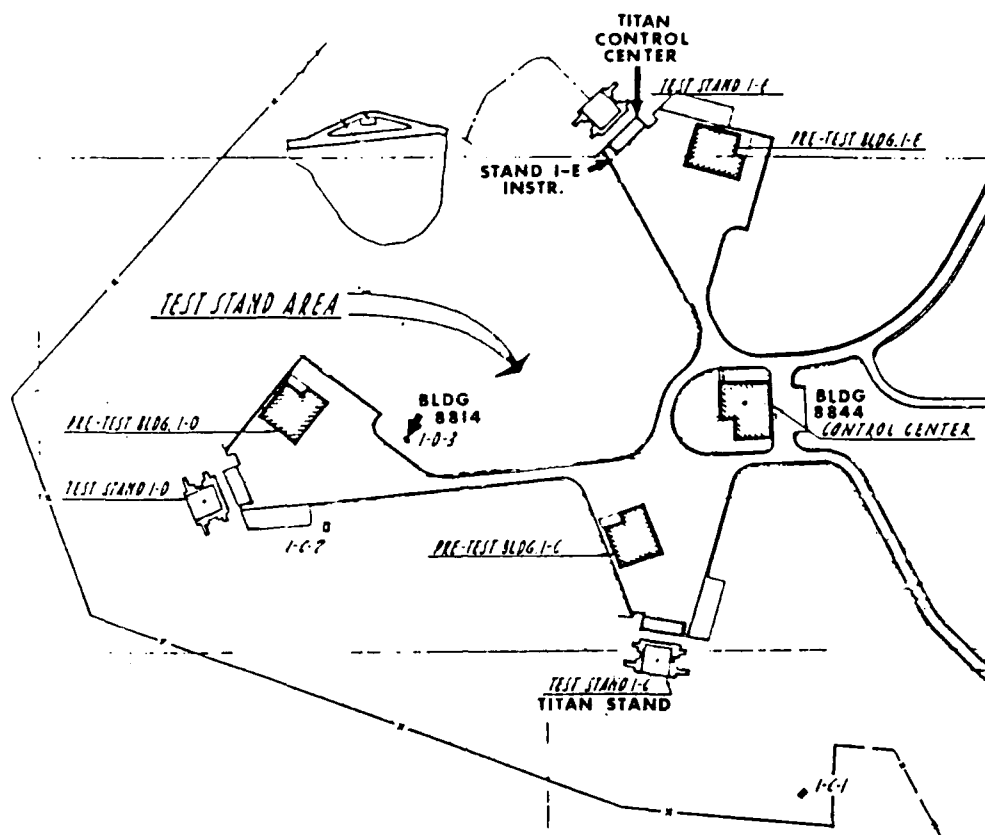
Figure 1. AFAL Experimental Area 1-125.

Area 1-125 was formerly used by Rockwell International's Rocketdyne Division during production testing of the F-1 liquid rocket engines that powered the Saturn V. The area had several large stands capable of handling the thrust of a full-scale Titan 34D SRM, and Thrust Stand 1-C was chosen to be modified for the test program. The stand, originally built for liquid engine testing using RP-1 and LOX, was modified to hold the 5-1/2 segment SRM nozzle-down (Figure 2). The water deluge system used during F-1 testing was re-serviced to provide cooling water to the exhaust deflector, or "flame bucket," during the test firing.

An environmental assessment was prepared and it was determined that the test would have no significant environmental impact. The assessment considered that the 5-1/2 segment SRM burns approximately 460,000 pounds of
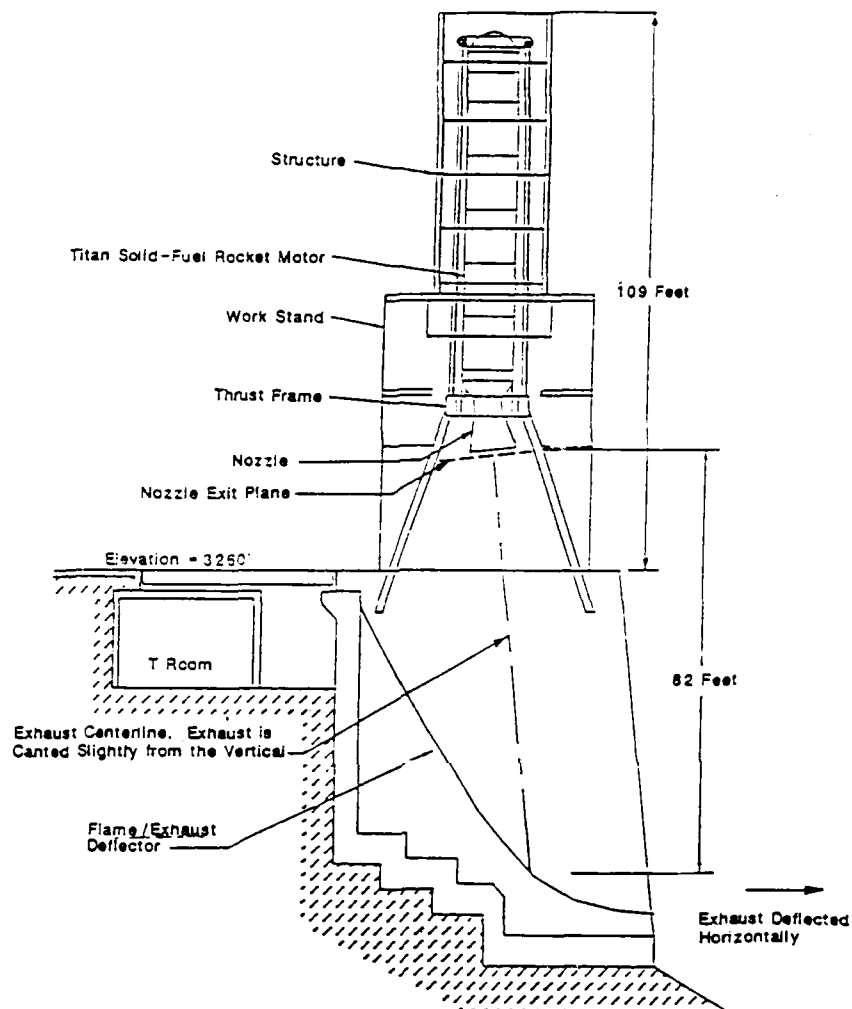
Figure 2. Thrust Stand 1-C configured for the Titan 34D firing.

propellant and produces the following exhaust constituents: HCl, aluminum oxide (Al_2O_3), carbon monoxide (CO), carbon dioxide (CO_2), water (H_2O), hydrogen (H_2), and nitrogen (N_2). Of the exhaust species, HCl is the most toxic. The assessment considered the dispersion of gaseous HCl and the mixing of the exhaust plume with buffered deluge water as well as other environmental concerns (Ref. 1).

The environmental monitoring program was developed to meet the following objectives:

..   Protection of personnel and equipment in the Control Center. The firing Control Center was located beneath Thrust Stand 1-E (shown in Figure 1) in the modified 1-E T-Room.

2.   Documentation of where the exhaust cloud passed over the Edwards AFB boundary and the actual ground-level concentrations of HCl from the exhaust.

3.   The study of the revolatilization process and the possibility of HCl regeneration from acidic rainout.

4.   Field-testing the Aerospace and AFESC/LLNL experimental HCl monitors.

The firing was first attempted on 4 June 1987; however, it was scrubbed that day and on three successive attempts because the weather conditions did not match requirements. On 15 June the test was successfully accomplished. The motor ignited at 1802 and burned out 120 seconds later, sending approximately 96,000 pounds of HCl into the air.

CONTROL CENTER AND TEST AREA MONITORING

INFILTRATION STUDIES

Two separate infiltration studies were conducted on buildings at Area 1-125. The facilities studied were Building 8844 and the Control Center (see Figure 1 and note that the original Area 1-125 Control Center is now referred to as Building 8844).   Building 8844 housed the computers used for data reduction during the firing. The Titan Control Center, located beneath Thrust Stand 1-E, housed the firing crew during the test.

Infiltration tests located sources of air infiltration (leakage) into the buildings by monitoring the concentration of a tracer gas in the building's atmosphere over a period of time. A known amount of tracer gas was injected into the building until a specific concentration was reached.   The concentration was continuously monitored and the rate at which the concentration decayed indicated the rate of infiltration of "clean" outside

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air into the building. For the studies performed at Area 1-125, Freon-22 (chlorodifluoromethane) was the tracer gas; its concentration was measured by a Miran 1A infrared spectro-photometer.

The first infiltration test was performed on 11 February 1987. The survey identified several leak sources in the buildings (e.g., broken seals on blast doors and air intake covers, open conduit pass-throughs) which were brought to the attention of the facility contractor (Ref. 2).

A second infiltration study was performed on 23 March 1987 to verify the effectiveness of repairs. The test confirmed that the infiltration rate had dropped to one-fourth that found during the previous test, and the facility was certified for use (Ref. 3).

MONITORING PROTOCOL

The closed environment of the Control Center presented special problems, problems that were discovered during the April 1986 Titan failure at Vandenburg AFB, CA. Following the loss of the vehicle, launch personnel were forced to remain in the Launch Operations Building because of burning solid propellant and brush fires. After a prolonged period of time, the air in the building became stagnant, forcing the personnel into the hazardous environment.

To prevent this type of incident from occurring during this and future tests, a monitoring protocol was developed for use in the Control Center during the course of the firing. The protocol examines the rate of depletion of oxygen and the rate of CO_2, temperature, and HCl buildup in the building, and compares them to the rate of HCl dispersion outside the building.

It was developed in response to the need to predict at what time it would be safe to exit the Control Center after the firing, and the need to predict when conditions in the Control Center might become dangerous. The same protocol was used at an October 1987 Titan launch and is proposed for use in all launch operations buildings.

THEORETICAL DEVELOPMENT

The protocol is based on the assumption that all of the changes in parameters are governed by exponential functions, i.e., that the basic equation governing the phenomena is

$$C = C_0 e^{kt} \tag{1}$$

where C is the function value at time t, C_0 is the original function value, and k is a mathematical constant (see Figure 3).
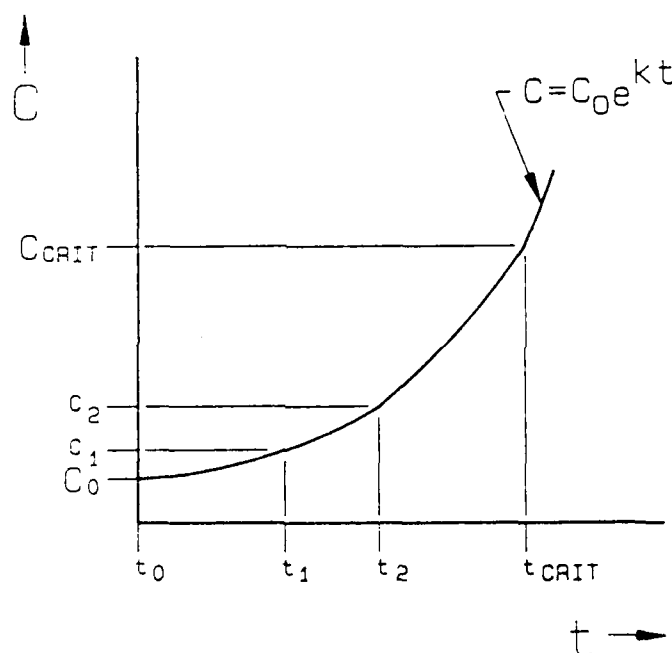
Figure 3. Simple exponential function.

Taking the natural logarithm of both sides gives

$$\ln(C) = kt * \ln(C_0) \tag{2}$$

and grouping the function values together leads to

$$kt = \ln\left(\frac{C}{C_0}\right). \tag{3}$$

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The equation can now be solved for the constant k,

$$k = \left(\frac{1}{t}\right)*\ln\left(\frac{C}{C_o}\right) \qquad (4)$$

or the time t,

$$t = \left(\frac{1}{k}\right)*\ln\left(\frac{C}{C_o}\right). \qquad (5)$$

As seen in Figure 3, discrete points t_1 and t_2 can be found corresponding to function values c_1 and c_2, respectively. According to this protocol, function values (c_x) correspond to the measurements of parameters taken at discrete times.

For the Titan Recovery Program test firing, the parameters were

    HCl(i) -- concentration of HCl in the Control Center,
    HCl(e) -- concentration of HCl outside the Control Center,
    CO_2 -- concentration of CO_2 in the Control Center,
    O_2 -- concentration of O_2 in the Control Center,
    T   -- measure of heat stress in the Control Center,
and safety -- a subjective parameter controlled by the Safety representative present.

Using the discrete points of measurements taken at specific times, an empirical value of the constant k, called k_e, can be calculated by the equation

$$k_e = \left(\frac{1}{t_2-t_1}\right)*\ln\left(\frac{C_2}{C_1}\right). \qquad (6)$$

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Care must be taken in applying this equation. For a more accurate estimate of the rate, the longest time interval available should be used (e.g., from t_0 to the time of the last measurement) in calculating the value of the constant k_e. However, in the analysis of the conditions in the Control Center, any perturbations in the rate (as might be caused by a fire in the room, a ventilation equipment breakdown, or the loss of seal integrity) must be taken into account; this was accomplished by calculating k_e over the increment of time between the two latest measurements.

Also shown in Figure 3, a critical value known as C_{crit} occurs at some future time from when the discrete readings are taken. The critical values for the parameters used in the monitoring protocol were:

$[HCl]_{crit}$ = 5 ppm (interior rising, exterior falling)
$[CO_2]_{crit}$ = 30,000 ppm (3%) (rising)
$[O_2]_{crit}$ = 18% (falling)
T_{crit} = 32.2 degrees C (WBGT) (rising).

The values for HCl, O_2, and T (thermal stress) are consistent with standard industrial hygiene practice; the value for CO_2 was established after consultation with Air Force flight surgeons.

The empirical constant k_e can be used to predict the time at which the function value will become critical:

$$t_{crit} = \left(\frac{1}{k_e}\right) * \ln\left(\frac{C_{crit}}{C_0}\right). \qquad (7)$$

If the last discrete measurement was made at time t_1, then the time until a critical value is reached would be

$$t(x) = t_{crit} - t_n \qquad (8)$$

where (x) is an identifier for whatever parameter is being studied, and t_n is the elapsed time from the original measurement (at t_0) to the last measurement, or $t_1 - t_0$.

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The protocol calls for such 'time-to-critical', or $t(x)$, calculations to be made for every parameter under investigation, then compared to one another to arrive at $t_{(int)}$, the time until a critical condition would be encountered in the Control Center interior, and $t_{(ext)}$, the time until the environment outside the Control Center would be free of contamination. $t_{(int)}$ is a function of all of the internal parameters as shown by

$$t_{(int)} = \text{minimum}(t_{HCl(i)}, t_{CO2}, t_{O2}, t_T, t_{safety}), \qquad (9)$$

i.e., the lowest of those critical times, while $t_{(ext)}$ equals $t_{HCl(e)}$.

Finally, the values of $t_{(int)}$ and $t_{(ext)}$ are compared, and the condition determined by the following criteria:

RED:	$t_{(int)} < 30$ min
ORANGE:	$t_{(int)} < t_{(ext)}$ (RED possible)
GREEN-HOLD:	$t_{(int)} > t_{(ext)} > 0$ min
GREEN-GO:	$t_{(ext)} = 0$ min (no RED possible).

A 'RED' condition would indicate a situation in which conditions inside the Control Center would deteriorate within thirty (30) minutes, meaning an emergency egress would have to be made using Self-Contained Breathing Apparatus (SCBA); an 'ORANGE' condition would indicate that while the interior conditions did not warrant emergency status, they would deteriorate faster than conditions outside would improve and SCBAs would still have to be used in a controlled egress. The 'GREEN-HOLD' condition would indicate that the environment outside the Control Center would clear faster than the environment inside deteriorated; a controlled egress without respiratory protection would be possible when the 'GREEN-GO' condition was reached, i.e., when the environment outside the Control Center was clear.

PROTOCOL IMPLEMENTATION

Instrumentation was set up in the Control Center to measure the parameters discussed previously. To measure HCl, a Geomet HCl Detector, Model 401B, was used. As backup to the Geomet, a long-term Draeger sampling tube

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was in place in a polymeter pump, and direct-reading Draeger tubes were available with a hand pump. Other HCl detection devices, placed in the Control Center by OEHL, were a midget impinger and a low-flow silica gel tube.

A Foxboro-Wilkes Miran 1A infrared spectrophotometer was used to monitor the level of CO_2 in the Control Center, and was backed up by a long-term Draeger tube in a second polymeter pump. To measure O_2, a Gastechtor combination explosive gas/oxygen meter was used. For heat stress measurements, a Reuter-Stokes Heat Stress Monitor was used to calculate the Wet Bulb Globe Temperature (WBGT).

For HCl concentration measurements outside the Control Center, a Geomet Model 401B was located at Thrust Stand 1-E. The Geomet output was connected to a stripchart recorder in the Control Center. This Geomet was backed up by another 401B located at a photo bunker (Building 8814); this second Geomet, intended to provide reference data for the LLNL experimental unit, was connected via modem to computer at the AFAL Safety Operations Center. Figure 1 shows the instrument locations at the test area.

HCl Monitoring, Inside. The Geomet in the Control Center was activated at 1214 and sampled the air until 2107. The instrument did not detect any HCl in the Control Center, indicating that no infiltration took place. Applying the principles of the monitoring protocol, the variable C_o (the original function value) was assigned the value of 0 ppm. Equation (7) relates the t_{crit} value to the natural logarithm (natural log) of the ratio of critical value to function value; for this case the ratio is 5/0.

The zero in the denominator drives the number to infinity; the natural log of the ratio also goes to infinity, making the t_{crit} (and subsequently the time-to-critical) value infinite for the interior HCl, or HCl(i). The equipment supplied by OEHL was activated at 1725, and analysis of the collection media indicated that no HCl was detected (Ref. 4). The long-term Draeger tube was not used.

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$\underline{CO_2\ Monitoring.}$ The Miran was activated at 1140 hours and operated continuously in the Control Center until shut off at 2104.   The Control Center was isolated at 1755 and not opened for two days.   Figure 4 shows a graph of the collected data, and Table 1 shows the t_{crit} values.
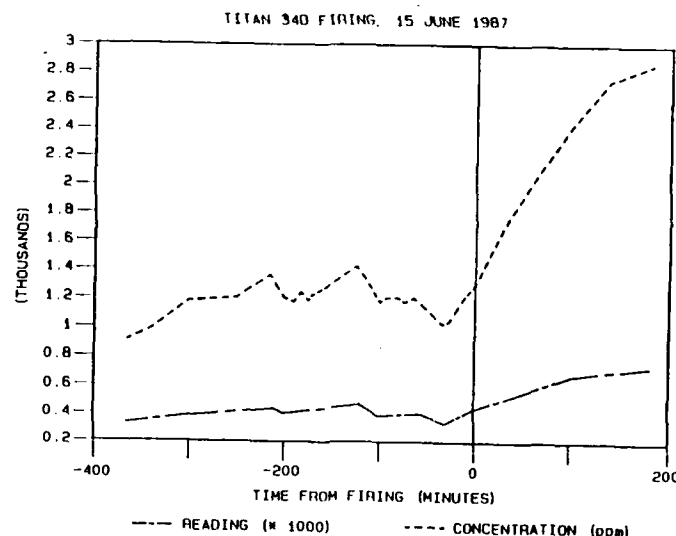
Figure 4. $\underline{CO_2\ measurements\ in\ the\ Control\ Center.}$

TABLE 1. CO_2 in the Control Center.   Concentration and t-critical.

Date: 15 June 1987   Location: 1-E Control Center

Instrument/Measuring: Miran 1A Spectrophotometer -- CO_2

Pressure   = 682.6 mm Hg
Temperature   = 294.4 K
Concentration = 0.195 * lambda

C_{crit} = 3% C_o = 1014 ppm T_o = 1730 $\ln(C_{crit}/C_o)$ = 3.3873

	Time (t)	Delta T	lamda/C	$\ln(C_i/C_{i-1})$	k_e	t_{crit}
1	1742	12	5400/1053	.0377	.0031	1077
2	1748	6	5800/1131	.0715	.0119	284
3	1758	10	6500/1268	.1139	.0114	297
	1802 - Firing Begins					
4	1814	16	7800/1521	.1819	.0114	297
5	1822	8	8300/1619	.0621	.0078	436
6	1830	8	8500/1658	.0235	.0029	1153

$k_e = \ln(C_i/C_{i-1})/\text{delta-t}$ $t_{crit} = \ln(C_{crit}/C_o)/k_e$

NOTES: 1) All time values are given in minutes except the local time in the first column.

2)   The Miran readings were fractions of a volt which were converted to 'lambda' by use of a calibration curve.   The values for lambda then had to be converted to concentration (C) in ppm by the relation given above.

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As shown, the lowest critical time value was 4.7 hours (284 minutes) and occurred at 1748 (fourteen minutes before the firing); using Equation (8), the time-to-critical, or t_{CO2}, at that time was 4.4 hours (266 minutes). The lowest t_{CO2} value, however, occurred at 1814, while the t_{crit} value was 5 hours (297 minutes). The elapsed time meant the t_{CO2} value was 4.2 hours (253 minutes). This indicates that personnel could only remain in the Control Center 4.2 more hours if the CO_2 buildup continued at the rate shown (0.0114 sec^{-1}). Again the long-term Draeger tube was available but not used.

O_2 Monitoring. The Gastechtor was activated approximately 12 hours prior to the firing, and registered the amount of O_2 in the air until 2111; Table 2 shows the data collected and the t_{crit} values. Oxygen readings were completely stable up to the controlled egress at 1840; between then and the final reading the O_2 concentration fell from 20.3 to 20.1 percent. Of course, by then the Control Center was unoccupied, so the t_{crit} value of 32.8 hours (1967 minutes) and the corresponding time-to-critical (t_{O2}) value of 29.1 hours (1745 minutes) have little meaning. This indicates that the amount of oxygen in the control room should not be a limiting factor in future tests unless an anomaly, such as a fire, occurs in the room.

TABLE 2. O_2 in the Control Center. Concentration and t-critical.

Date: 15 June 1987   Location: 1-E Control Center

Instrument/Measuring: Gastechtor -- O_2

C_{crit} = 18% C_o = 20.3% T_o = 1729 $\ln(C_{crit}/C_o)$ = -.1202

	Time (t)	Delta T	C	$\ln(C_i/C_{i-1})$	k_e	t_{crit}
1	1741	12	20.3	zero	zero	inf
2	1747	6	20.3	zero	zero	inf
3	1757	10	20.3	zero	zero	inf
	1802 - Firing Begins					
4	1814	17	20.3	zero	zero	inf
5	1822	8	20.3	zero	zero	inf
6	1829	7	20.3	zero	zero	inf
	1840 - Controlled Egress					
7	2111	162	20.1	-.0099	-.0001	1967

$k_e = \ln(C_i/C_{i-1})/\text{delta-t}$ $t_{crit} = \ln(C_{crit}/C_o)/k_e$

NOTES: 1) All time values are given in minutes except the local time in the first column.
2) Underlined values were not calculated on the day of the firing, as the Control Center was already vacant.

Heat Stress Monitoring. The Reuter-Stokes unit was activated about 12 hours before the firing and ran until 2112. Data and t_{crit} values for the indoor WBGT are shown in Table 3. As shown, the most remarkable change in the thermal stress while the room was occupied occurred between 1746 and 1756, with a corresponding t_{crit} value of 9.1 hours (545 minutes). Taking into account the elapsed time, the time-to-critical (t_T) value was 8.6 hours (514 minutes). The final reading, taken at 2112 after the Control Center had been evacuated, resulted in a t_{crit} value of 5.8 hours (345 minutes) and a t_T value of 2 hours (119 minutes). As with the O_2 buildup, this time-to-critical value is meaningful only as an indication of the trend and had no operational impact since the room was vacant.

TABLE 3. WGBT in the Control Center. Reading and t-critical.

Date: 15 June 1987   Location: 1-E Control Center

Instrument/Measuring: Reuter-Stokes Heat Stress Monitor -- WBGT(in)

C_{crit} = 305.4 K C_o = 294.3 K T_o = 1725 $\ln(C_{crit}/C_o)$ = .037

	Time (t)	Delta T	C	$\ln(C_i/C_{i-1})$	k_e	t_{crit}
1	1739	14	294.4	.0003	2.4267E-5	1525
2	1746	7	294.4	zero	zero	inf
3	1756	10	294.6	.0007	.0001	545
	1802 - Firing Begins					
4	1813	17	294.7	.0003	1.9964E-5	1853
5	1821	8	294.7	zero	zero	inf
6	1829	7	294.7	zero	zero	inf
	1840 - Controlled Egress					
7	2112	163	299.9	.0175	.0001	345

k_e = $\ln(C_i/C_{i-1})$/delta-t t_{crit} = $\ln(C_{crit}/C_o)/k_e$

NOTES: 1) All time values are given in minutes except the local time in the first column.
    2) Values for 'C', the indoor Wet Bulb Globe Temperature, are in degrees Kelvin.
    3) Underlined values were not calculated on the day of the firing, as the Control Center was already vacant.

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HCl Monitoring, Outside. The Geomet located at Thrust Stand 1-E was activated at 1810; however, due to an oversight data from the instrument did not start recording until 1837. For this reason, data had to be relayed by telephone from the Safety Operations Center to the Control Center; the data was generated by the Geomet and Interscan at Building 8814 and was transmitted to Operations over the LLNL modem hookup. Because the concentration outside the Control Center dropped off rapidly, t_{crit} calculations were begun but not continued; it was decided to go ahead with the egress procedure when the concentration dropped below 5 ppm. The concentration dropped below that critical value at 1839. Comparisons of the t_{crit} values (but not the time-to-critical values) calculated are shown in Table 4. The test conductor was made aware of the environmental conditions and controlled egress procedures were initiated at 1840.

TABLE 4. t-critical comparisons and condition evaluations.

Date: 15 June 1987   Location: 1-E Control Center

$HCl_{i\ crit}$ = 5 ppm (up) $[CO_2]_{crit}$ = 30 000 ppm (up)
$HCl_{e\ crit}$ = 5 ppm (down) $[O_2]_{crit}$ = 18% (down)
                                                 T_{crit} = 32.2 deg C

	Time	HCl$_i$	CO$_2$	O$_2$	T	safe	$t_{crit(i)}$	$t_{HCl(e)}$	Cond
1	1742	n/a	1077	inf	1525	inf	1077	n/a	n/a
2	1748	n/a	284	inf	inf	inf	284	n/a	n/a
3	1758	n/a	297	inf	545	inf	297	n/a	n/a

1802 - Firing Begins

4	1814	inf	297	inf	1853	inf	297	anomaly	G-H
5	1827	inf	436	inf	inf	inf	436	n/a	G-H
6	1833	inf	1153	inf	inf	inf	1153	n/a	G-H

1840 - Controlled Egress

NOTES: 1) All time values are given in minutes except the local time in the first column.
           2) 'inf' means infinite.

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HCl sampling was accomplished during the egress procedure using Draeger direct-reading tubes. The areas through which the egress took place had not been continuously monitored, and the first people to egress wore SCBAs because of the unknown concentration of HCl. Seven negative samples were taken during the egress maneuver, so the test conductor decided to go ahead with the general egress of Control Center personnel.

TEST AREA MONITORING

As mentioned previously, Geomet HCl Detectors were placed at Thrust Stand 1-E and Building 8814 (refer to Figure 1). HCl detection equipment placed at Thrust Stand 1-E by OEHL consisted of a large impinger and high-and low-flow silica gel tubes. OEHL placed the same type of equipment plus a midget impinger at Building 8814. The Aerospace Corporation located their experimental HCl monitor at Thrust Stand 1-E, and LLNL placed their experimental unit and an Interscan Compact Portable Analyzer at Building 8814.

Thrust Stand 1-E. As mentioned, the Geomet at this location was activated at 1810 but its data collection did not begin until 1837. Because the Geomet produces time-resolved data, the data regarding the HCl concentrations found immediately after the test was lost. A plot of the data is shown in Figure 5. The plot shows that for as long as three hours after the test firing, an HCl concentration of 0.1 ppm was present; this HCl concentration is attributed to revolatilization (off-gassing) of HCl from the deposition of acidic rainout. Analysis of their sampling media indicated that OEHL's impinger and low-flow silica gel tube detected no HCl, while their high-flow tube detected 7.9 ppm (2-minute average) (Ref. 4). The Aerospace unit failed, apparently due to a power surge.

Building 8814. The Geomet at this location was activated at 1725 and pegged immediately after the 1802 firing. Set on the 0-10 ppm scale, any concentration of HCl over that would cause the Geomet to read 10 ppm until the concentration dropped below that level. The Interscan placed at Building 8814 by LLNL read a peak value of 62.4 ppm; a plot of the Geomet and Interscan readings is given in Figure 6. (It is interesting to note that prior to the

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TITAN 34D FIRING 15 JUNE 1987
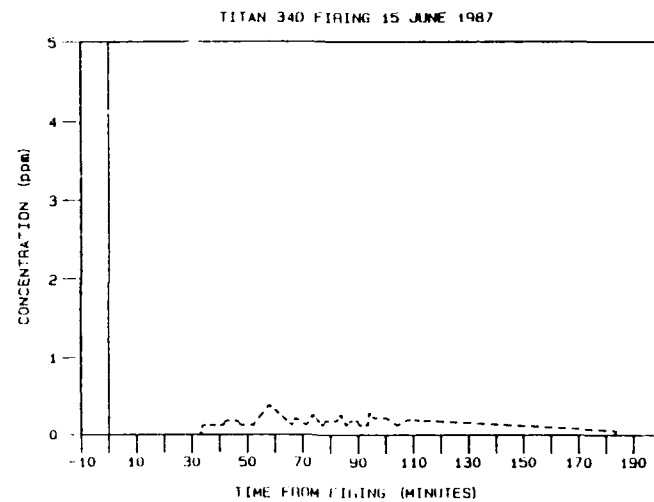
Figure 5.   HCl measurements at Thrust Stand 1-E.

firing the Geomet registered 0.0 ppm of HCl while the Interscan was reading an average of 0.61 ppm.)   OEHL's analysis of their sampling media indicated that their equipment detected the following levels of HCl (2-minute averages):

Large Impinger	204 ppm
Midget Impinger	744 ppm
High-Flow Silica Gel Tube	137 ppm
Low-Flow Silica Gel Tube	234 ppm (Ref. 4).

TITAN 34D FIRING, 15 JUNE 1987
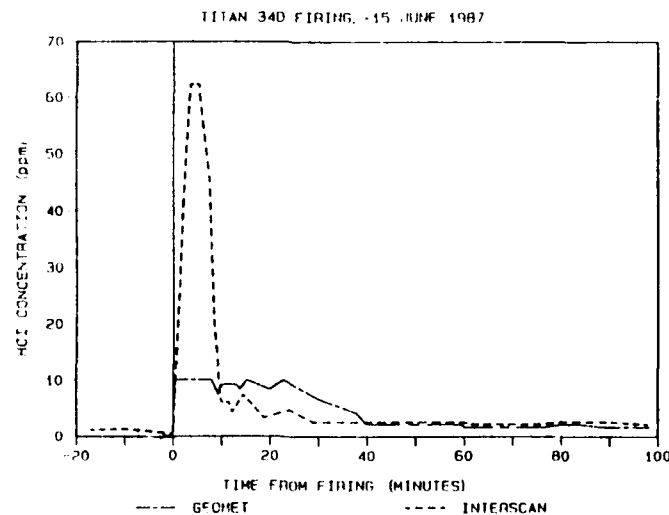
Figure 6.   HCl measurements at Building 8814.

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The LLNL experimental unit failed to operate properly because depositions from the exhaust cloud impacted its mirrors, blocking the infrared beam.

DOWNRANGE MONITORING

METEOROLOGICAL DATA COLLECTION

Because of the amount of propellant being burned in the Titan 34D firing, special meteorological constraints were required, especially with regard to wind direction. The environmental assessment specified a wind corridor of 260 - 310 degrees azimuth, which is shown in Figure 7. (Ref. 1)

Figure 7. Wind corridor for the Titan 34D firing.

Air Weather Service Detachment 21 provides meteorological support for the Air Force Flight Test Center and the AFAL. In supporting the AFAL they rely mainly on the AFAL Automaetic Weather System (AWS), shown in Figure 8. The AWS is a network of instrumented towers spread across the AFAL. These towers record wind velocity. delta-T (the difference in temperature between points 6

and 54 feet above the ground), humidity, and barometric pressure and relay the information to the AFAL Safety Operations Center. There the data is displayed on a terminal and is used to support rocket motor tests and other hazardous operations.
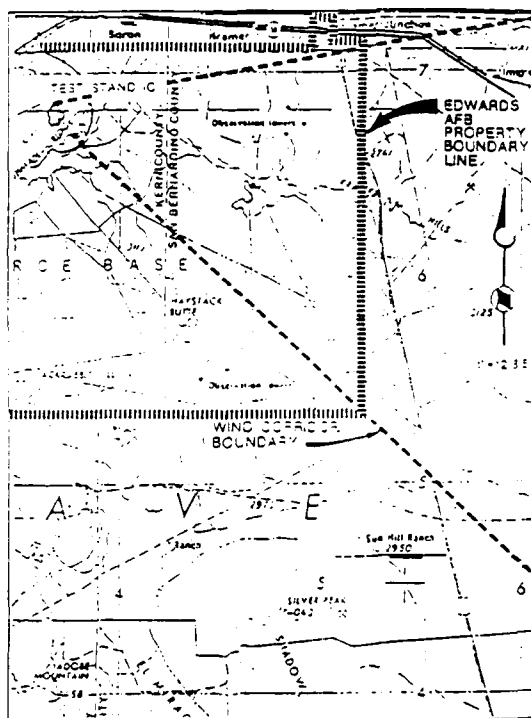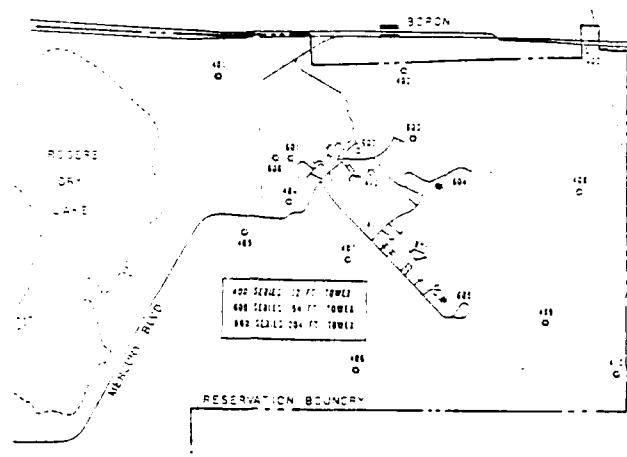

Figure 8. AFAL automatic weather system.

The meteorological support for the Titan test, however, was more extensive. Winds aloft were considered in establishing go/no-go criteria, making the use of weather balloons necessary. Air Weather Service Det 21 launches rawinsonde balloons daily in its regular support operations, and the data from these balloons was relayed to Operations. On the first day the Titan test was attempted, Det 21 also sent up pilot balloons on a regular basis, relaying the data to the AFAL Safety Operations Center.

When the first firing attempt was scrubbed, it was surmised that the meteorological information might not be accurately reflecting the conditions at the AFAL. All balloon launches had been taking place at the rawinsonde site at Edwards main base, over twelve miles across Rogers Dry Lake from AFAL Area 1-125. It was decided to launch the pilot balloons from AFAL Area 1-36 for all other firing attempts, in order to obtain wind data more representative of AFAL winds. Figure 9 illustrates balloon launch points, and Table 5 gives the wind data collected on the day of the firing.
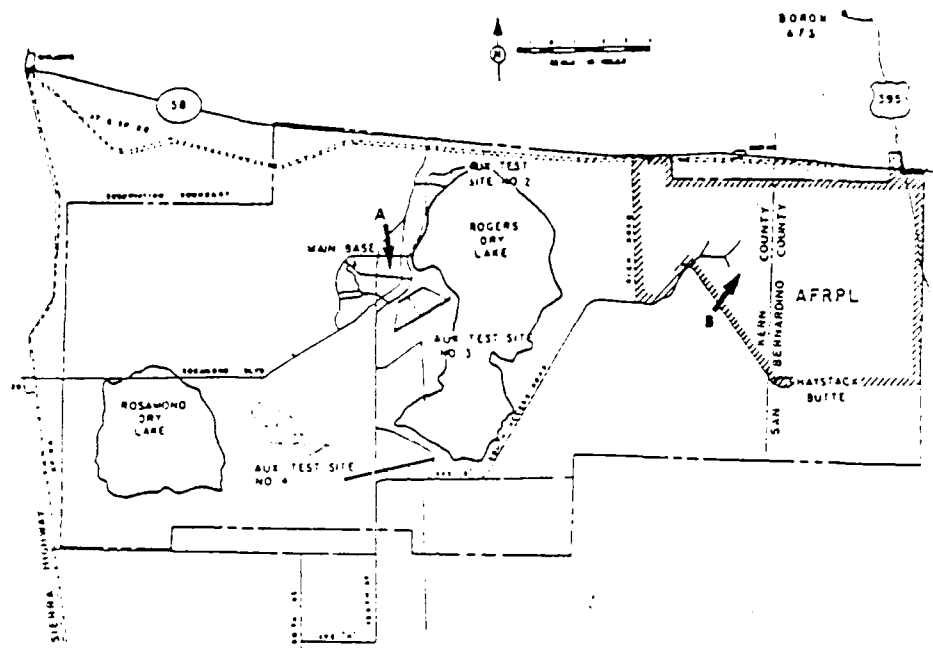
Figure 9.   Weather balloon launch sites.
A - Edwards AFB rawinsonde site.
B - AFAL Area 1-36.

TABLE 5.   Wind data, 15 June 1987.

Wind directions (degrees azimuth) and speeds (knots)
with respect to time and height above the ground.

					Height above ground level (feet)							
Time	12	1K	2K	3K	4K	5K	6K	7K	8K	9K	10K	Mean	
1234L	280	260	250	240	250	250	260	270	260	260	250	257	deg
	22	16	18	26	28	28	29	31	31	33	41	27	kts
1305L	250	260	260	250	250	240	250	250	260	250	250	252	deg
	15	40	33	19	36	29	30	25	28	33	37	29	kts
1335L	240	250	260	260	250	240	250	250	250	250	250	250	deg
	14	15	12	15	19	24	28	32	33	35	36	24	kts
1408L	250	240	250	260	260	250	250	250	250	260	260	254	deg
	13	17	20	24	26	26	33	36	41	42	46	29	kts
1445L	280	260	260	250	250	250	240	250	250	260	260	256	deg
	20	33	32	20	21	22	19	33	45	54	53	32	kts

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TABLE 5.   Wind data, 15 June 1987 (concluded).

Wind directions (degrees azimuth) and speeds (knots)
with respect to time and height above the ground.

Time	12	1K	2K	3K	4K	5K	6K	7K	8K	9K	10K	Mean	
1518L	250	250	260	260	260	250	250	260	250	250	250	253	deg
	15	20	20	19	21	20	29	33	38	41	45	27	kts
1548L	250	260	260	270	270	270	260	240	250	260	250	258	deg
	25	20	24	28	36	31	25	24	37	43	43	30	kts
1618L	260	260	270	270	280	260	250	260	260	250	250	260	deg
	15	23	25	23	26	26	23	38	38	36	35	28	kts
1649L	250	250	250	270	270	260	260	260	260	250	250	257	deg
	16	25	29	24	24	21	27	34	27	40	39	28	kts
1721L	260	260	270	270	270	280	260	260	260	260	250	263	deg
	14	33	28	24	23	26	22	34	40	39	35	29	kts

SAMPLING STRATEGY

Atmospheric and dispersion modeling experts from NASA's Marshall Space Flight Center and from The Aerospace Corporation attempted to predict the dispersion of HCl from the static firing. Their predictions had a high degree of uncertainty, however, due to the complex chemical reactions between the exhaust plume and the buffered deluge water and the complex windflow patterns around Leuhman Ridge.

Because accurate HCl dispersion predictions were not available, downrange sampling was designed to take advantage of the specified wind corridor, and provided for both near-field and far-field sampling of ground-level HCl concentrations. The sampling scheme called for three near-field sampling sites (AFAL Experimental Areas 1-90, 1-100, and the Receiving, Inspection and Storage (RIS) Building), three far-field sites (Askania camera sites 1-A, 2-A, and 3-A), and a number of sites along the base boundary and near local communities. These sites are shown in Figure 10, and their instrumentation and sampling results are presented in Table 6.
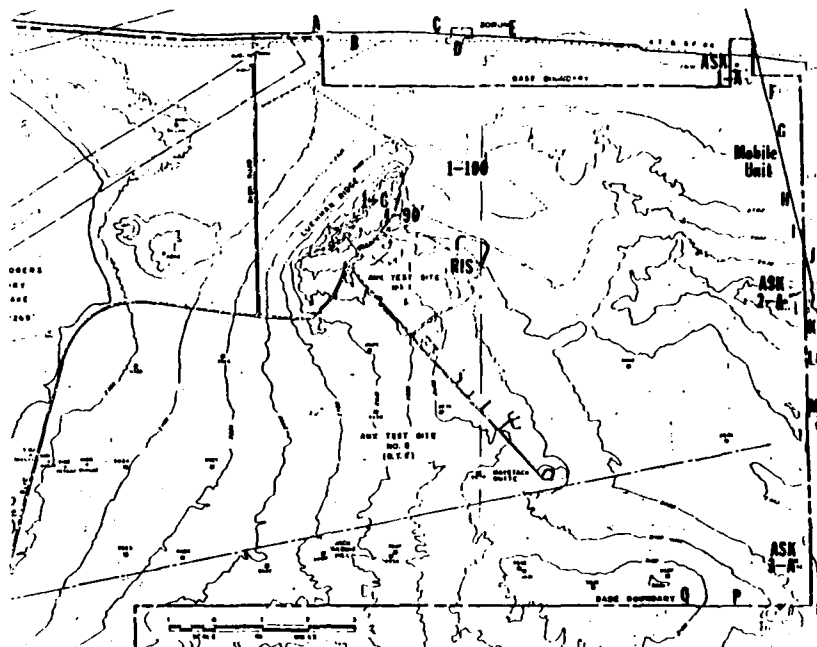
Figure 10. Downrange sampling locations.

TABLE 6. Downrange sampling results.

Designation/ Location	Equipment	Responsible Agency	Results
Area 1-90	Geomet	AFAL/SD	Equip Fail
	Interscan	OEHL	0.4 ppm (peak)
	Large Impinger	OEHL	ND
	High Flow Tube	OEHL	ND
Area 1-100	Geomet	AFAL/SD	ND
	Interscan	OEHL	0.02 ppm (peak)
	Large Impinger	OEHL	ND
	High Flow Tube	OEHL	ND
RIS Bldg	Geomet	AFAL/SD	0.3 ppm (5 min)
	Interscan	OEHL	0.69 ppm (peak)
	Large Impinger	OEHL	ND
	High Flow Tube	OEHL	ND
Askania 1-A	Geomet	AFAL/SD	0.1 ppm (1 min)
	Interscan	OEHL	Equip Fail
	Midget Impinger	OEHL	3.2 ppm
	High Flow Tube	OEHL	ND

TABLE 6. Downrange sampling results (concluded).

Designation/ Location	Equipment	Responsible Agency	Results
Askania 2-A	Geomet	AFAL/SD	ND
	Interscan	OEHL	Anomaly
	Large Impinger	OEHL	ND
	Midget Impinger	OEHL	ND
	High Flow Tube	OEHL	ND
Askania 3-A	Geomet	AFAL/SD	ND
	Interscan	OEHL	ND
	Large Impinger	OEHL	ND
	Midget Impinger	OEHL	ND
	High Flow Tube	OEHL	ND
Mobile Unit	Interscan	OEHL	0.12 ppm (peak)
	Large Impinger	OEHL	ND
	Midget Impinger	OEHL	2.8 ppm
	High Flow Tube	OEHL	ND
Boundary Samplers			
A	High Flow Tube	OEHL	ND
B	High Flow Tube	OEHL	ND
C	High Flow Tube	OEHL	ND
D	High Flow Tube	OEHL	ND
E	High Flow Tube	OEHL	ND
F	High Flow Tube	OEHL	ND
G	High Flow Tube	OEHL	ND
H	High Flow Tube	OEHL	ND
I	High Flow Tube	OEHL	ND
J	High Flow Tube	OEHL	ND
K	High Flow Tube	OEHL	ND
L	High Flow Tube	OEHL	ND
M	High Flow Tube	OEHL	ND
N	High Flow Tube	OEHL	ND
O	High Flow Tube	OEHL	ND
P	High Flow Tube	OEHL	ND
Q	High Flow Tube	OEHL	ND

Notes: 1. ND means 'none detected.' It does not indicate that no HCl was present, it merely notes that none was detected: HCl may have been present below the limit of the particular equipment. For instance, 'ND' on a Geomet would indicate that HCl may have been present, but the concentration would have to be below 0.01 ppm.

2. Values for the midget impingers are 10-minute time-weighted-averages as determined by the appropriate NIOSH analytical method.

The accuracy of the Askania 1-A and mobile unit readings are questionable. According to the analysis of the sampling media in the OEHL impingers, the HCl concentration at these sites was 3.2 and 2.8 ppm, respectively (10-minute average) (Ref. 4). The Geomet at Askania 1-A only registered 0.1 ppm for approximately one minute, and the mobile Interscan detected a similarly low value. In addition, the lack of physical evidence casts doubt on these results. The odor threshold of gaseous HCl is listed as 1-5 ppm (Ref. 5), but physical responses have been documented at concentrations as low as 0.067 ppm (Ref. 6). Experience has shown that the presence of HCl can be detected below 1 ppm because of its irritating effects; therefore, it is logical to assume that the personnel located at Askania 1-A and in the mobile unit would be able to sense the HCl at the levels indicated at these sites. However, the personnel at Askania 1-A neither smelled anything resembling HCl nor felt any discomfort, and the personnel who were in the mobile unit disagree on what they sensed: one claims that he sensed nothing, the other that he caught "a faint wiff" of the gas (Ref. 7).

PHOTOGRAPHIC COVERAGE

The environmental monitoring effort of the Titan firing was supported by two types of photographic coverage. Photographic tracking of the exhaust cloud as it passed over the test area was provided by the Air Force, and The Aerospace Corporation provided computer-enhanced visible and infrared imagery of the exhaust plume. Locations of the photographic equipment used are shown in Figure 11.

EXHAUST CLOUD TRACKING

Contravi tracking mounts at four surveyed locations tracked the exhaust cloud as it moved away from the stand. The cameras photographed the cloud at a rate of five frames per second and were trained on the cloud's highest point. Disagreement between the camera operators as to where the highest point was (the cloud being very tenuous as it dissipated) made it difficult to plot the cloud's ground track. A plot was ultimately produced, but it only tracked the cloud 400 feet downwind.
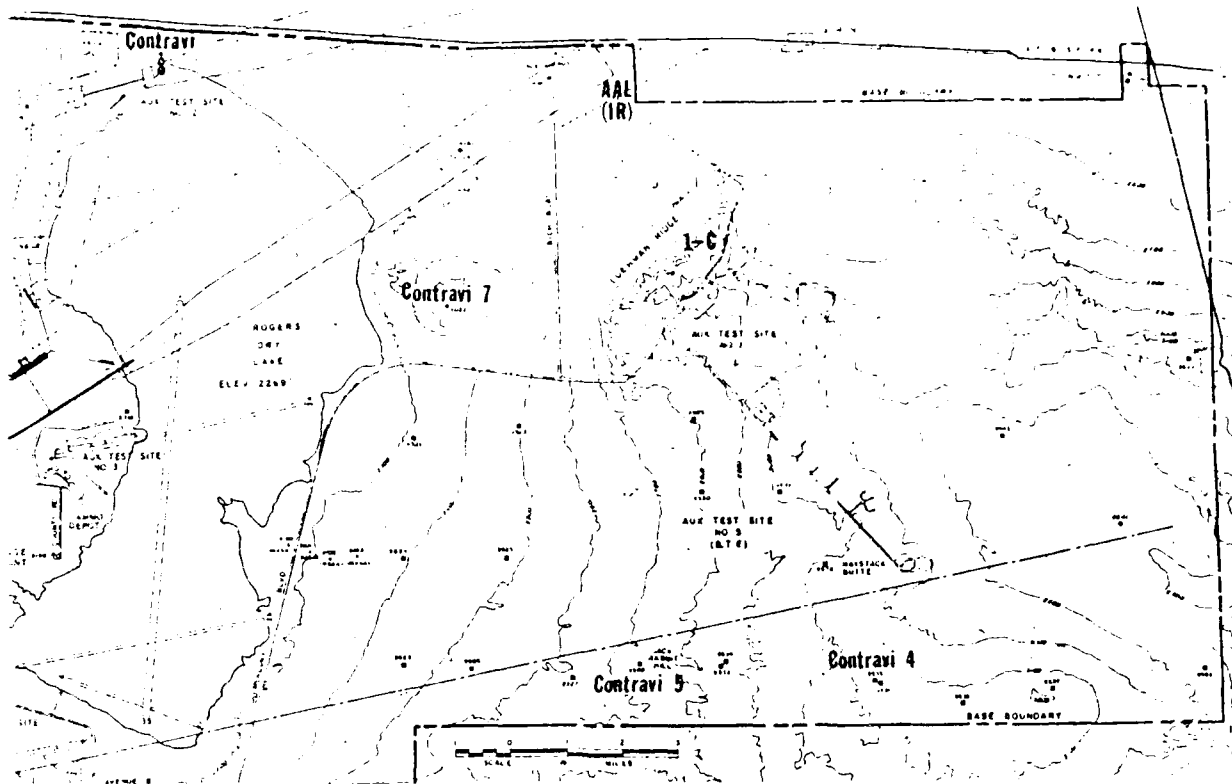
Figure 11. *Photographic coverage locations.*

Two things precluded being able to track the exhaust cloud as it traveled further downrange. The first was the rate at which the Contravi cameras photographed the cloud: five frames per second was too fast for tracking the slow-moving cloud (the Contravi mounts are typically used for tracking aircraft missions). The second was the rate at which the cloud dissipated. Within minutes of the firing it was difficult to pick out the cloud against the sky. Thus the only way to mark at what point the cloud passed over the base boundary was from the position of the mobile sampling unit.

The cloud stabilized at approximately 2000 feet above ground level (AGL), dissipating as it moved eastward. Mobile unit personnel estimated the position of the cloud and placed themselves under it. Their position on Highway 395 was approximately one mile south of Kramer Junction; extrapolating their position back to Area 1-125, it was found that the cloud remained in the wind corridor specified in the Environmental Assessment.

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Photographic coverage by The Aerospace Corporation produced the pictures of the development of the ground cloud shown in Figures 12a-c. The photographic sequence shows how quickly the cloud formed and how completely it inundated the valley below Thrust Stand 1-C.
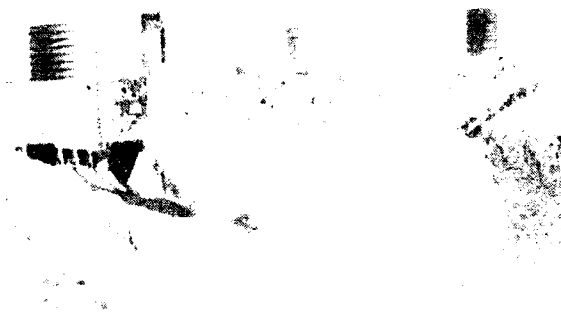

Figure 12a. Ground cloud formation. (T + 1 second)
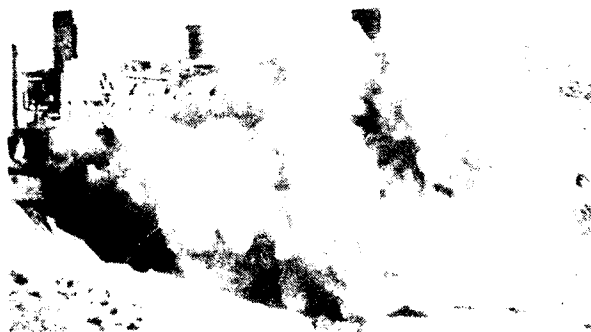(Photo courtesy The Aerospace Corporation)

Figure 12b. Ground cloud formation. (T + 4 seconds)
(Photo courtesy The Aerospace Corporation)

Figure 12c. Ground cloud formation. (T + 15 seconds)
(Photo courtesy The Aerospace Corporation)

COMPUTER IMAGERY

Located north of Area 1-125 near an old clay mine, The Aerospace
Corporation set up visible and infrared imagery cameras, along with computer
equipment for data reduction and storage. The infrared camera was equipped
with a special filter tuned to the absorption wavelength of HCl, which made it
feasible to register the HCl apart from the other constituents of the exhaust
plume. Both the visible imagery of the exhaust plume and the infrared imagery
of the HCl in the plume were recorded on video discs.

The effectiveness of the enhancement technology is shown in Figures 13
through 15. Figures 13a-e are a regular photographic sequence of the exhaust
plume, again showing the massive ground cloud completely obscuring the test
area and the rapid dissipation of the cloud.

Figure 13a. Titan 34D exhaust plume. (T + 10 seconds)
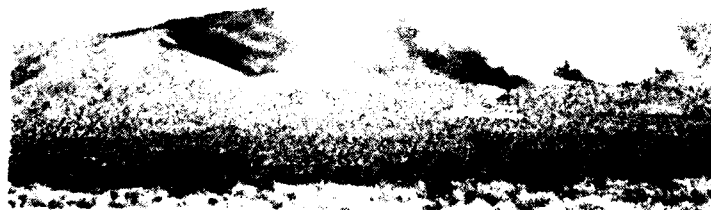(Photo courtesy The Aerospace Corporation)

Figure 13b. Titan 34D exhaust plume. (T + 1 minute)
(Photo courtesy The Aerospace Corporation)

Figure 13c. Titan 34D exhaust plume. (T + 2 minutes)
(Photo courtesy The Aerospace Corporation)

Figure 13d. Titan 34D exhaust plume. (T + 2 minutes, 30 seconds)
(Photo courtesy The Aerospace Corporation)

Figure 13e. Titan 34D exhaust plume. (T + 3 minutes)
(Photo courtesy The Aerospace Corporation)

Figure 14 consists of a sequence of computer-generated pictures of the firing. Figures 14a-c are "unsubtracted" images, i.e., the background can still be clearly seen. Figures 14d-f are images in which the computer has subtracted the background. The final result is shown in Figure 14f, in which the entire background has been subtracted; the dark area in the image is the area affected by rainout from the exhaust cloud.

Figure 14a. Visible imagery of the Titan 34D exhaust plume.
(Visible unsubtracted, T + 1 minute)
(Photo courtesy The Aerospace Corporation)

Figure 14b. Visible imagery of the Titan 34D exhaust plume.
(Visible unsubtracted, T + 2 minutes)
(Photo courtesy The Aerospace Corporation)

Figure 14c. Visible imagery of the Titan 34D exhaust plume.
(Visible unsubtracted, T + 3 minutes)
(Photo courtesy The Aerospace Corporation)
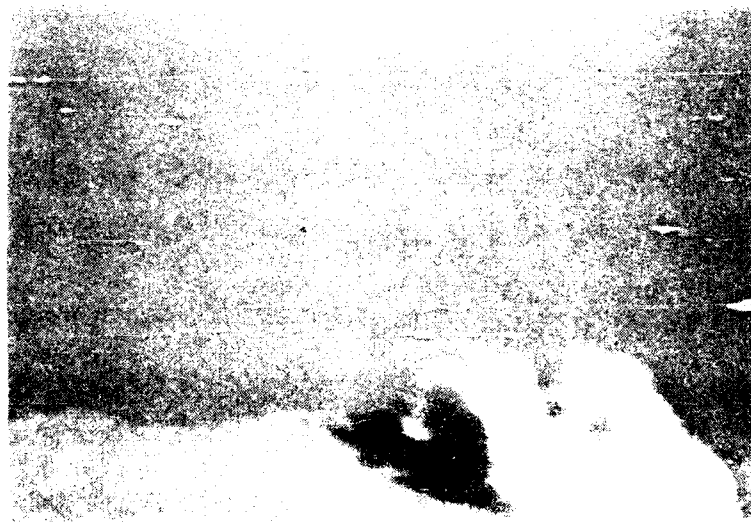

Figure 14d. Visible imagery of the Titan 34D exhaust plume.
(Visible subtracted, T + 1 minute)
(Photo courtesy The Aerospace Corporation)

Figure 14e. Visible imagery of the Titan 34D exhaust plume. (Visible subtracted, T + 2 minutes) (Photo courtesy The Aerospace Corporation)

Figure 14f. Visible imagery of the Titan 34D exhaust plume. (Visible subtracted, T + 14 minutes) (Photo courtesy The Aerospace Corporation)

Figure 15 displays the infrared imagery of the HCl and water aerosol in the plume with the background subtracted. In Figure 15a the lightest areas are probably hot HCl gas emission; the faint outline of the exhaust cloud can be seen, while the densest concentration of HCl appears to be directly over the test area. In Figure 15b the HCl cloud has moved downrange and the exhaust cloud boundary has become less distinct as the cloud dissipated. In Figure 15c the background has greyed for better contrast and the image is similar to Figure 14f; the dark splotch is the part of the hill on which the cloud rained out and the white spot is the area of heaviest HCl deposition below the stand, which remains extremely hot due to HCl reaction with the soil. Figure 15d, taken closer to the time of Figure 14f, shows the dynamics of the HCl reaction. Comparing Figures 15d and 15c, it is seen that both the large dark area and the bright spot below the test area have grown smaller and less distinct, indicating that some of the HCl in the rainout has reacted or revolatilized. Comparing Figures 15d and 14f, it is clear that the rainout is still present although the acid has off-gassed.

Figure 15a. Infrared imagery of the Titan 34D exhaust plume.
(IR subtracted, T + 2 minutes, 30 seconds)
(Photo courtesy The Aerospace Corporation)

Figure 15b. Infrared imagery of the Titan 34D exhaust plume.
(IR subtracted, T + 3 min.)
(Photo courtesy The Aerospace Corporation)

Figure 15c. Infrared imagery of the Titan 34D exhaust plume.
(IR subtracted.
(Photo courtesy The Aerospace Corporation)

Figure 15d. Infrared imagery of the Titan 34D exhaust plume.
(IR subtracted, T + 12 minutes, 30 seconds)
(Photo courtesy The Aerospace Corporation)

REVOLATILIZATION

ROCKET EMISSIONS ANALYSIS FACILITY

In a cooperative effort between SD and the AFAL, the Rocket Emissions
Analysis Facility (REAF) was established at the AFAL in the Spring of 1987.
The facility contains space for the calibration of instrumentation used in
monitoring static firings and launches. The focal point of the facility is
the revolatilization chamber, a small wind tunnel used to study the
revolatilization (off-gassing) of materials from surfaces representative of
those at operational sites under controlled conditions of wind speed,
humidity, temperature, and solar flux. A layout of the REAF is shown in
Figure 16.

HCl REGENERATION

Local soil was collected from Area 1-125 for revolatilization studies.
The purpose of the study was to examine the reaction between HCl solution and
local soil, and to predict the strength of revolatilization from soil
representative of the test area. The soil used in the study was gathered from
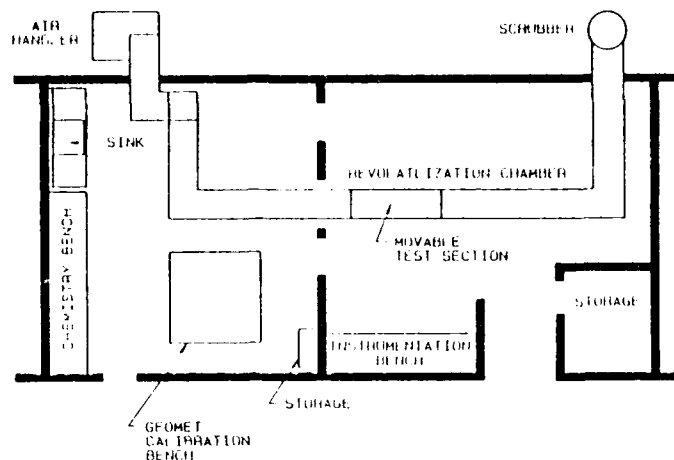near Building 8814.

Figure 16. Rocket Emissions Analysis Facility layout.

The soil was packed into the test section of the revolatilization chamber and was deluged with a 5.0 molal solution of HCl. The reaction between the acid and the alkaline soil was immediate, the soil changing from its usual tan color to a dull yellow; the soil displayed a high degree of buffering capability. The density of the soil changed in the reaction, from 1.49 g/cc to 1.41 g/cc.

The strength of HCl revolatilization is measured using two Geomet HCl Detectors, one upstream and one downstream of the chamber's test section, as shown in Figure 17. During the 2 June 1987 pre-firing revolatilization run, the upstream Geomet registered a constant 0.0 ppm, indicating that no HCl was circulating back into the system; a plot of the downstream Geomet results is given in Figure 18. The strength of revolatilization was found to be 0.074 g HCl per minute per square meter of surface area. Based on that figure, the expected HCl concentration in the breathing zone over the deposition area due to revolatilization was 1.7 ppm.

DEPOSITION COLLECTION

Eight specially-designed collection pans, each 9 ft^2, were fabricated from stainless steel for this project and coated to resist the effects of the acid. The pans, shown in Figure 19, were placed strategically around the test
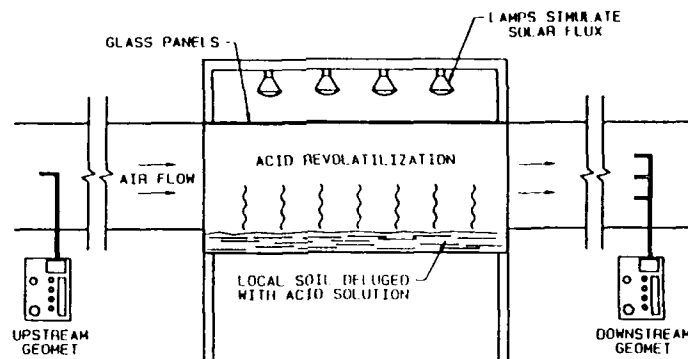
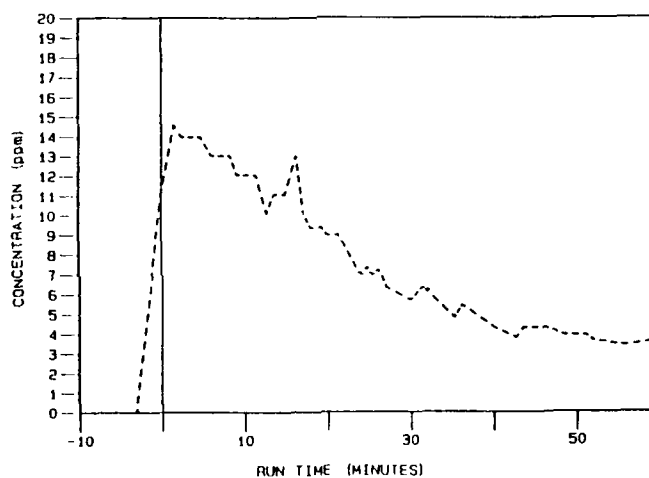Figure 17.   Revolatilization chamber test schematic.

RUN TIME (MINUTES)

Figure 18.   Revolitilization strength measurements.
Downstream concentration of HCl during the 2 June 1987 revolitilization run.

area as shown in Figure 20, with two pans placed at each location.   The pans were filled approximately one inch deep with light paraffin oil (mineral oil), which acted as an evaporation inhibitor by allowing depositions to fall to the bottom of the pan while the oil floated on top.

Large amounts of deposition were collected in the pans at Thrust Stand 1-E, Building 8814, and the containment trench, but the pans downhill of the test article (Site A of Figure 20) were flooded with mud.   The Site A pans had not been affected during combined systems tests when the deluge water system was run, but the added momentum of the exhaust plume drove the deluge water
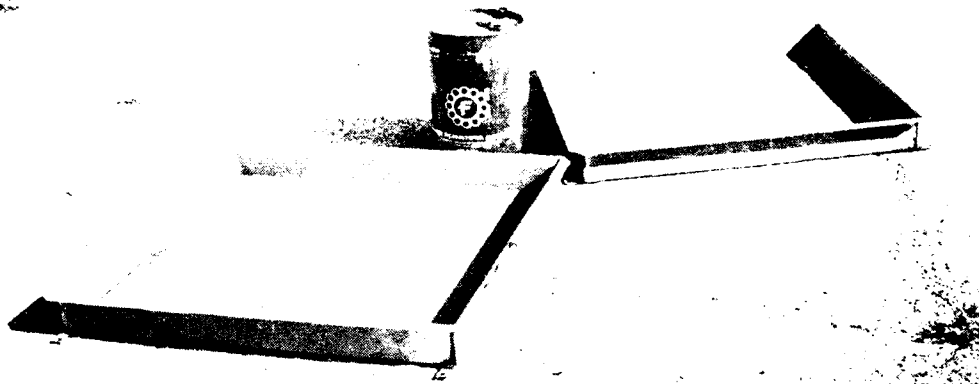
35

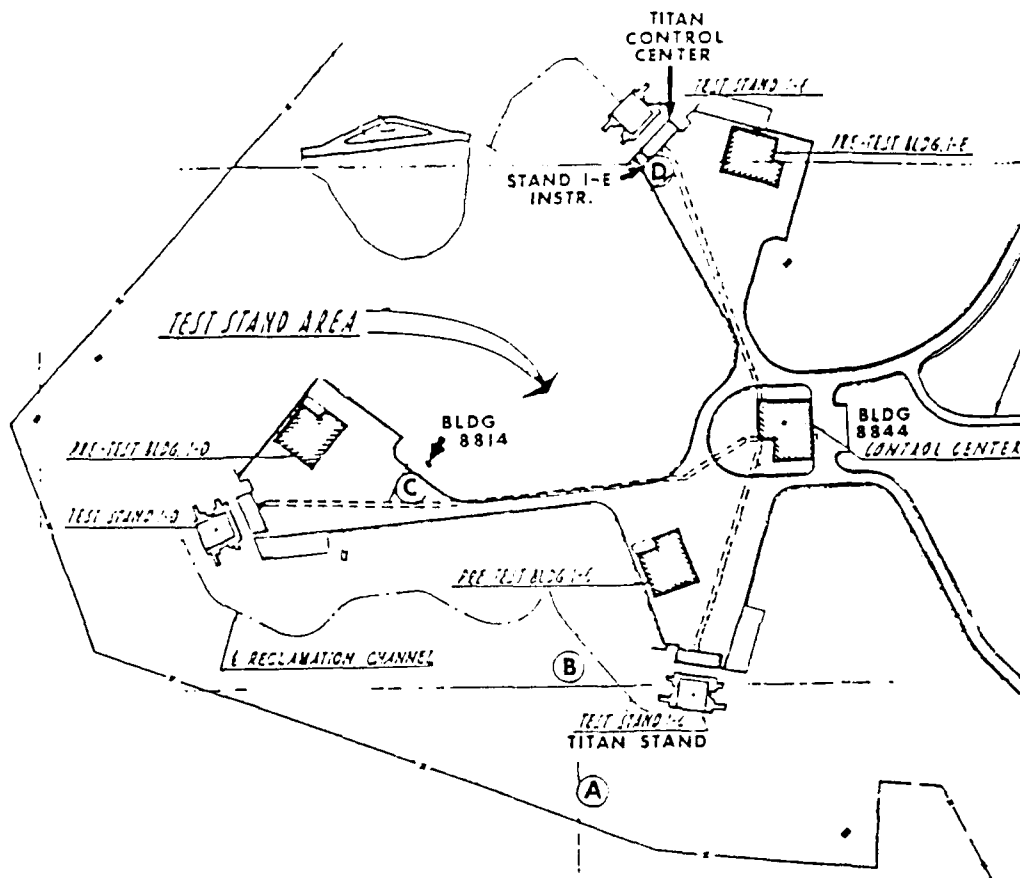Figure 19. Deposition collection pans with a can of mineral oil.

Figure 20. Placement of the collection pans.
A - Downhill from the test article.
B - Containment trench.
C - Building 8814.
D - Thrust Stand 1-E.

further out from the stand than anticipated, flooding the pans with acidic mud washed down from the hill below the stand. The other sets of pans collected nearly an order of magnitude more deposition than that caught at Cape Canaveral from Shuttle launches. The amount of rainout collected and the pH of the deposition at each site was:

Site	Mass Loading $(1/m^2)$	pH
Containment Trench	7.87	1.10
Building 8814	8.38	1.91
Thrust Stand 1-E	9.91	3.31.

A graph of the above data is shown in Figure 21. Note that as the pans got further away from the test article, more deposition was caught and the deposition became less acidic.
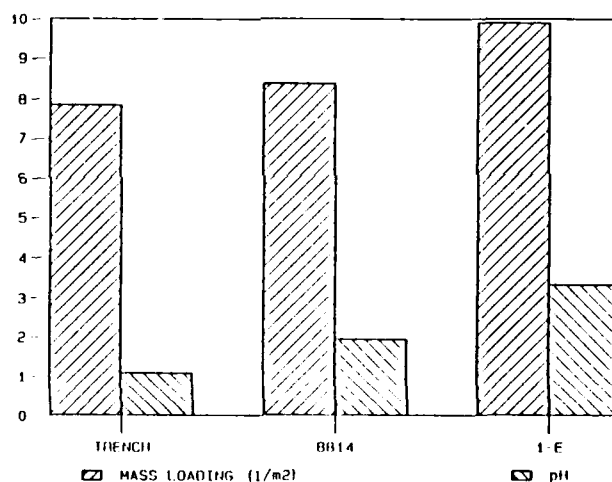

Figure 21. Deposition mass loading and pH.

As shown, the pH of the depositions was fairly high, indicating weakly acidic solutions. It is postulated that the pans caught large amounts of the buffered deluge water that was blasted away from the stand and rained-out in the area without contacting the majority of the HCl plume. This water significantly diluted the samples; a revolatilization study was performed with some of the depositions collected after the firing, but no revolatilization was observed due to the weak acidity of the samples.

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The valley in front of Thrust Stand 1-C was inundated with acidic rainout and deluge water. In addition to flooding the collection pans placed below the stand, the viscous green rainout reacted with the valley soil, turning it a bright yellow. A week later the deposition coloration had faded to a dull yellow, much different from the soil color prior to the firing. The second color change is thought to have been caused by gradual chemical reaction of the deposition with the soil.

Supporting this theory, in addition to the infrared imagery provided by The Aerospace Corporation, are HCl measurements taken after the firing. At Building 8844 the concentration of HCl the day after the firing was 0.1 ppm at midday; by late afternoon the concentration had dropped to 0.02 ppm. At Building 8814, located in the path of visible deposition, a 0.5 ppm concentration of HCl was detected the day after the firing. Two days after the firing the concentration of HCl at Building 8844 varied between 0.01 and 0.02 ppm. Acid vapors could still be smelled two days after the firing and the smell of HCl persisted for a week due to revolatilization of available unreacted HCl.

INSTRUMENTATION

GEOMET HCL DETECTOR

The Geomet HCl monitor works on the chemiluminescence principle. An air sample is drawn into the instrument through an alumina tube coated with a mixture of sodium bromate and sodium bromide; HCl in the incoming gas stream reacts with the mixture to form hypochlorite and hypobromite and is drawn into contact with an alkaline solution of 5-amino-2, 3-dihydro-1, 4-phthalazinedione (luminol). The hypochlorite and hypobromite initiate oxidation of the luminol, producing visible light. The light intensity is directly proportional to the concentration of HCl in the air sample and is converted via a photomultiplier tube into an output voltage which can be recorded on a stripchart (Ref. 8). Geomet samplers are illustrated in Figure 22; an operational schematic is shown in Figure 23.
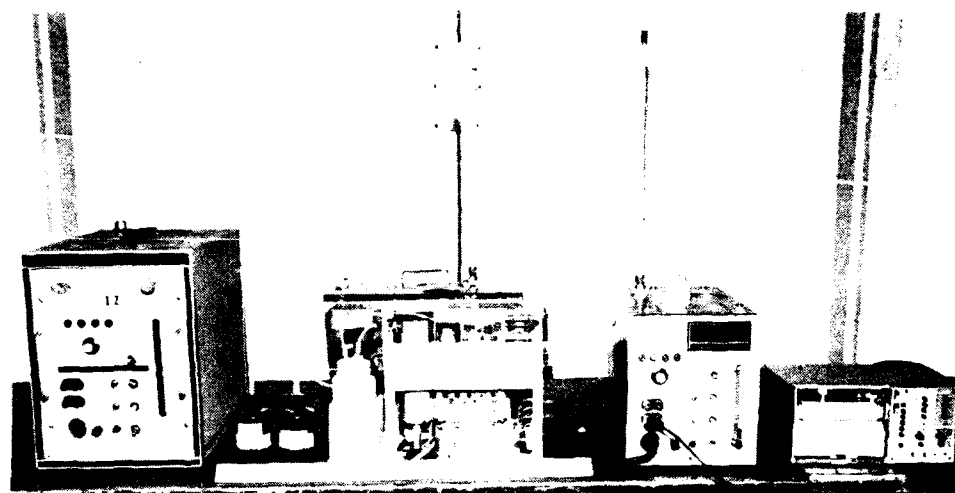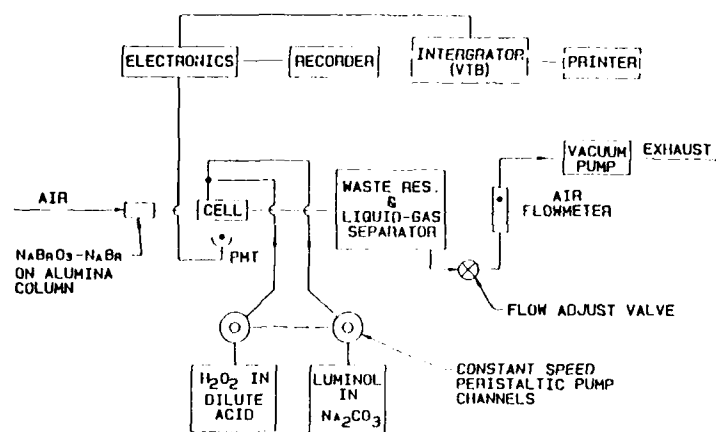
Figure 22. Geomet HCl detectors.
Left to right: Model 401S, Model 401B with cover removed (side view),
Model 401B with stripchart recorder.

PMT = PHOTOMULTIPLIER TUBE

Figure 23. Geomet operational schematic.

The Geomets used in this project were Model 401Bs, as well as older Model 401Ss. They were calibrated using a G-Cal ovenless calibrator, with which a known concentration of gas is pumped into the Geomet and the instrument is adjusted until its readout corresponds to the known concentration. Problems encountered in calibrating with HCl gas in previous studies (Ref. 9) led to the use of the G-Cal unit using chlorine gas. Chlorine may be substituted for HCl in the calibration process because the responses are identical.

INTERSCAN COMPACT PORTABLE ANALYZER

The Interscan is an electrochemical detector in which the air sample passes through a diffusion medium after which the gaseous molecules are adsorbed on the sensing element. The element is an electrode on which the molecules are electrochemically reacted; the reaction produces an electric current which is directly proportional to the concentration of HCl in the sample (Ref. 10). An Interscan is shown in Figure 24.
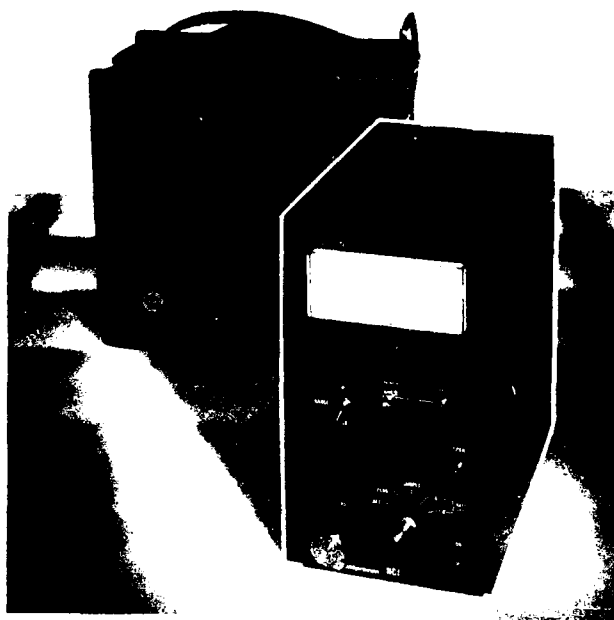

Figure 24.   Interscan compact portable analyzer.

OEHL and LLNL used Interscans during the monitoring project, but the LLNL unit was actually on loan to them from OEHL. The OEHL Interscans were calibrated with HCl using a MAST permeation system set up in the REAF.

IMPINGERS

Impingers are absorption samplers consisting of glass bottles in which contaminated air is bubbled through a liquid reagent. Figure 25 shows impingers like those used by OEHL to sample for HCl.

The midget impinger is a gas washing bottle in which air is simply bubbled through the liquid; no additional mixing of the gas and the reagent is

accomplished.   Such impingers are typically used to sample for gases that
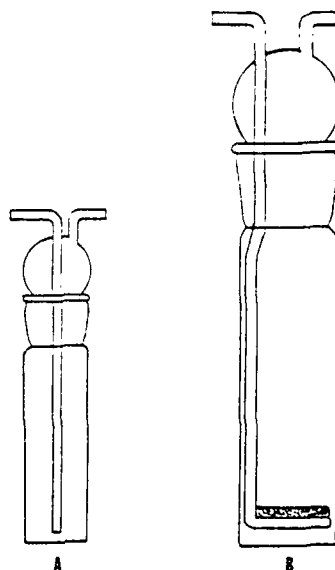react readily with the reagent (Ref. 11).

Figure 25.   Impingers.   A - Midget impinger. B - Large impinger.

The large impinger is a fritted bubbler, characterized by the passage of
the air through a frit, a porous glass plate.   The frit causes the gas to form
small bubbles in the liquid, increasing the mixing of the gas and the reagent.
Because of the mixing action, the large impinger is typically more efficient
than the simple bubbler.   Large impingers are also used for gases that react
well with the sampling media (Ref. 11).

OEHL used distilled water as the sampling media in all of its impingers
and used DuPont sampling pumps to pull their samples.   The pumps were
calibrated and the samplers prepared in the REAF (Ref. 4).

SILICA GEL TUBES

Contrasted with the impinger (an absorption device), the silica gel tube
is an adsorption sampler.   Adsorption samplers are typically glass tubes
(either straight or U-shaped) filled with an adsorbent, usually activated
charcoal or silica gel (Ref. 11).

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The sampling effectiveness of silica gel tubes is dependent on the mesh size of the gel, ambient humidity and temperature, and the rate of airflow (Ref. 11). OEHL used DuPont sampling pumps to draw air through their tubes and used two tubes operating at different flow rates in critical areas (Ref. 4).

DRAEGER TUBES

Draeger detector tubes are a proven method for making on-the-spot measurements of the concentrations of atmospheric contaminants. They consist of a glass tube through which an air sample is drawn with a pump, the tubes are filled with a reagent which reacts with the suspect contaminant. The amount of the contaminant in the air is indicated by a color change in the reagent; the length of the color change is directly related to the concentration. Draeger tubes are calibrated and indicate the concentration given a specific amount of air that must be sampled (Ref. 12). Figure 26 shows Draeger detector tubes and their associated pumps.
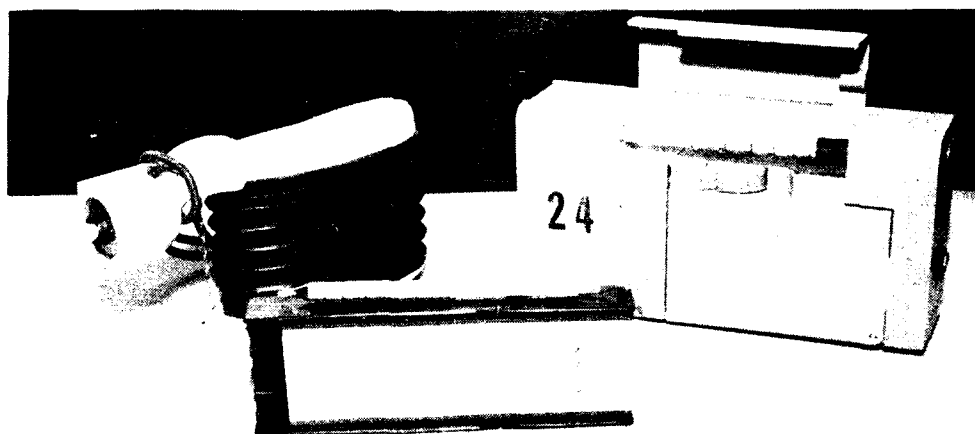

Figure 26. Draeger tubes and pumps.
Foreground: HCl tube with box of tubes.
Background: (left to right) hand pump, polymeter pump.

The tubes used in this study were HCl short-term tubes and HCl and CO_2 long-term tubes. Short-term tubes are typically used with a hand pump that pulls 100 mL of air through the tube per stroke, while long-term tubes are used with automatic pumps that count the number of revolutions of the pump. While short-term tubes are read directly to obtain the concentration, long-term tubes require that a series of calculations be performed to obtain the

results, and while short-term tubes indicate the instantaneous concentration, long-term tubes indicate the average concentration over the sampling period (Ref. 12).

THE AEROSPACE CORPORATION HCl MONITOR

The experimental unit placed at Thrust Stand 1-E consisted of an infrared detection system housed in a nitrogen-purged enclosure. The detector scanned with an infrared laser diode tuned to a single rotational line of HCl, measuring the concentration of HCl by how much of the IR beam was absorbed. The system used PVC pipe attached to a ladder to pull in air from approximately thirty feet above the detector; a port in the PVC took the air into the detector. A schematic of the system is shown in Figure 27.
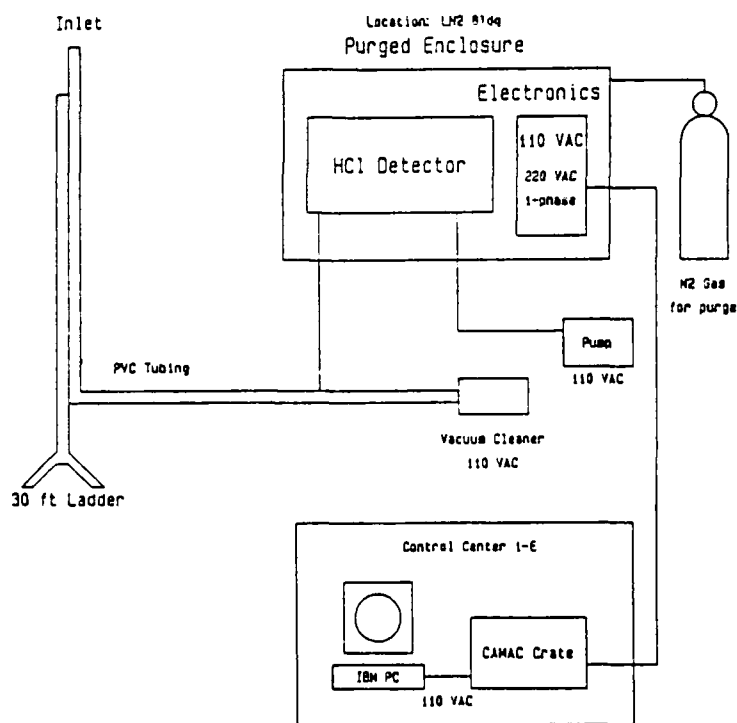

Figure 27. Aerospace HCl monitor schematic.

The CAMAC crate shown in the figure provided data translation so the data could be recorded on the computer. The video display would show that HCl was present, but it could not display quantitative data.

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Apparently a power surge occurred around the time of the firing, causing the laser diode power supply to automatically shut down. Consequently, the Aerospace unit was unable to measure the amount of HCl present at Thrust Stand 1-E.

LAWRENCE LIVERMORE NATIONAL LABORATORY HCl MONITOR

The unit placed at Building 8814 by LLNL was a prototype of an HCl detector proposed for measuring HCl at Vandenberg AFB launch sites. The unit operated on the principle of dispersive IR absorption, in which the infrared radiation is separated into a reference band and a sample band, as shown in Figure 28a. The sample band corresponded to the absorption wavelength of HCl; the reference band was chosen so the presence of HCl would not affect it and is used to take into account any electronic, mechanical, or thermal effects that may affect the sample signal (Ref. 13).
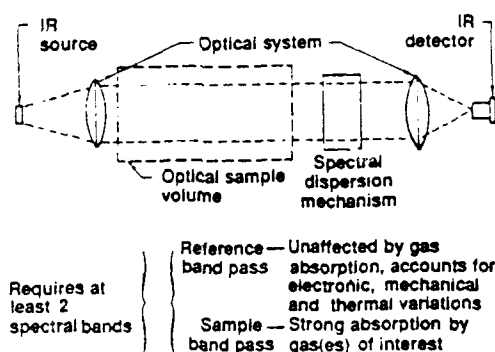

Figure 28a. Lawrence Livermore HCl monitor dispersive IR absorption operating principle.

The data acquisition system (DAS) for the LLNL detector is shown in Figure 28b. The sensor head was hung about two meters off the ground outside Building 8814, while the sensor electronic unit and the remote DAS station were inside the building. The remote DAS station was connected to the central station through the use of modems and a standard telephone line; the central station was located at the Safety Operations Center.
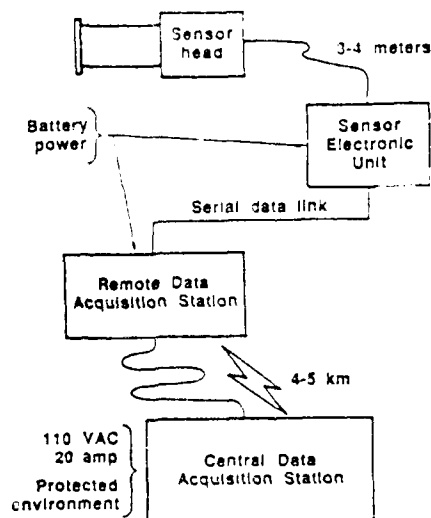
Figure 28b. Lawrence Livermore HCl monitor
data acquisition system schematic.

The detector was operated during every firing attempt, as well as on the day of the test. The equipment operated properly every day and tests of the data transmission system indicated that the modem hookup is a practical and effective method of connecting the remote unit to the central DAS station. The unit's operation during the firing was spoiled by deposition which impacted the optical mirrors, preventing the signal from completing the optical path; thus the unit could not register the amount of HCl at Building 8814.

MIRAN 1A INFRARED SPECTROPHOTOMETER

The Miran 1A portable gas analyzer is a single beam spectrophotometer that scans the infrared range of 2.5 to 14.5 microns. It has a 5.6 liter Teflon-coated gas cell with a variable beam path length from 0.75 to 20.25 meters. The unit is illustrated in Figure 29. The Miran, like the Aerospace and LLNL detectors, operates on the principle that specific compounds absorb infrared radiation at specific wavelengths (Ref. 14).

Calibration of the Miran is accomplished with a bellows pump plumbed into the detector cell. Measured amounts of gas are injected into the system

through a septum, and the deflection of the instrument noted. The concentration of the gas in the detector cell is calculated knowing the capacity of the cell and the amount of gas injected, and is corrected for temperature and pressure. A calibration curve is developed from which the ambient concentration can be obtained given the deflection of the instrument (Ref. 15).
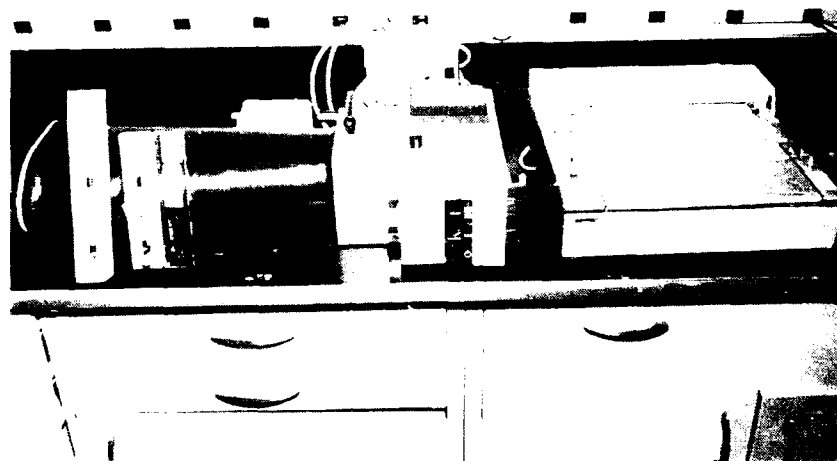

Figure 29. Miran 1-A and calibration equipment.
Front to back, left to right: calibrated syringes,
Miran 1-A stripchart recorder, bellows pump.

For use in the Control Center, the Miran had to be calibrated for CO_2. The ambient concentration of CO_2 (0.033% or 330 ppm) caused some problems during the calibration, so the instrument was purged with nitrogen and calibrated with a purged gas cell. After calibration the Miran was purged again and the cell closed; the cell was not opened until sampling was to start.

GASTECHTOR

A Model 1214MP Gastechtor Gas Alarm was used in the Control Center to monitor the level of oxygen in the room. Its oxygen sensor is an electrochemical cell consisting of gold and lead electrodes in an alkaline electrolyte; the sensor is covered by a permeable membrane. Oxygen diffuses

through the membrane and is electrochemically reacted to form lead oxide. The rate of the reaction (and the current generated by the reaction) is directly proportional to the partial pressure of oxygen (Ref. 16). A Gastechtor is pictured in Figure 30.
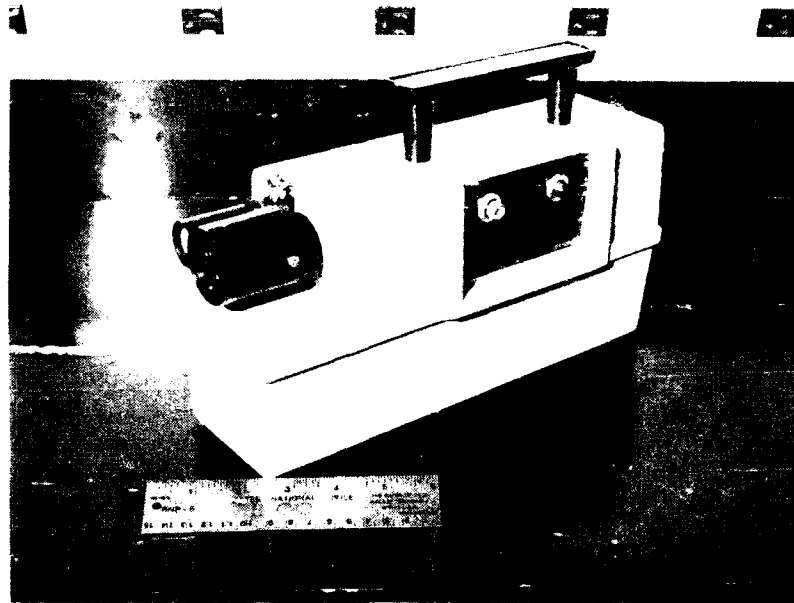

Figure 30. Gastechtor oxygen and combustible gas meter.

REUTER-STOKES HEAT STRESS MONITOR

The Wet Bulb Globe Temperature index (WBGT) is used to evaluate the heat stress conditions present in the working environment and is determined by using a dry bulb thermometer, a natural (static) wet bulb thermometer and a globe thermometer. The dry bulb must be shielded from the sun and the wet bulb wick kept wet with distilled water. The globe thermometer consists of a hollow copper sphere painted matte black on the outside with a temperature sensor fixed at the center of the sphere. The WBGT is calculated from the temperature readings; for WBGT inside a building (or outside with no solar loading) the equation is:

$$WBGT = 0.7 \ WB + 0.3 \ GT \tag{10}$$

where WB is the wet bulb temperature and GT is the globe temperature. The dry bulb temperature is only used for calculating the outdoor WBGT (Ref. 17).

The Reuter-Stokes Model RSS-217 Heat Stress Monitor and Logger was used in the Control Center during the firing. The unit takes temperature measurements and calculates the WBGT automatically, displaying either the indoor or outdoor WBGT at the operator's discretion. Figure 31 shows the Reuter-Stokes 'Wibget' unit.
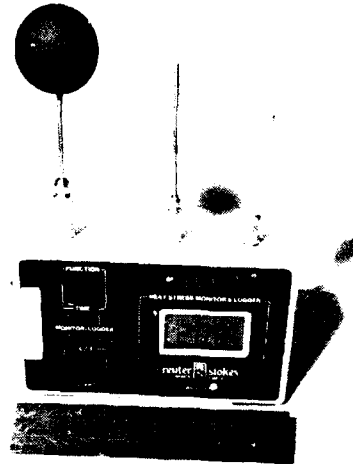

Figure 31. Reuter-Stokes Heat Stress Monitor.

CONCLUSIONS AND RECOMMENDATIONS

Operational and physical precautions taken at Area 1-125 included strict procedures for shutting down ventilation and sealing the buildings prior to and personnel egress after the firing, infiltration studies, and repairs to area facilities to reduce the chance of HCl contamination. The precautions proved effective in protecting personnel and equipment in the Control Center and Building 8844 from the high HCl concentrations generated by the test. The same precautions should be taken during future tests of this magnitude.

The gaseous HCl that passed over the base boundary was concentrated in the exhaust cloud, the ground-level concentrations encountered posed no threat to public health. Although it must be noted that other meteorological conditions might have caused very different dispersion of the HCl, there is no evidence that future tests of this magnitude should be hindered in any way for environmental reasons as long as similarly prudent constraints are considered. Future tests should, of course, be accompanied by similar monitoring efforts.

The decision that all winds up to 10,000 feet AGL had to be within the corridor proved to be too strict. Future test wind criteria should be limited to 5000 feet AGL, as this test proved that the exhaust cloud remains stable and relatively low-level.

The overall wind corridor was effective in keeping the exhaust cloud from passing over nearby population centers; however, time-resolved (real time) meteorological data was not available. It is quite possible that windows of opportunity were missed while waiting for balloons to be launched and their data reduced at discrete intervals; thus data-gathering for future tests should be carefully considered. The use of acoustic sounders, Doppler Lidar, and wind tracers might prove cost-effective if operational windows can be better identified and utilized.

The disparities in results among different sampling devices makes it difficult to evaluate their applicability to monitoring this and similar tests. Programs to compare the performance of HCl monitors have typically concentrated on laboratory evaluations; comparative studies in monitoring actual field operations have been rare. A program should be initiated to further study HCl sampling devices to determine which performs best in field applications.

The wind flow over the complex terrain of the AFAL should be studied and modeled in an effort to better understand the transport of gaseous contaminants, and to relax the wind restrictions imposed on this type of test. A study of this type may produce information applicable to conditions at the Western Space and Missile Center at Vandenberg AFB or the Eastern Space and Missile Center at Cape Canaveral.

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REVOLATILIZATION CALCULATIONS

Revolatilization test calculations are made by considering the test section as a control volume as shown in Figure A-1. The mass flow into and out of the control volume is written as

$$m_1 + m_2 = m_3 \tag{A-1}$$

where m_1 represents the mass of HCl flowing into the control volume from the upstream side,

m_2 represents the mass of HCl flowing into the control volume from the control surface, and

m_3 represents the mass of HCl flowing out of the control volume. Thus if m_1 and m_3 are known, m_2 can be calculated and is the strength of revolatilization.
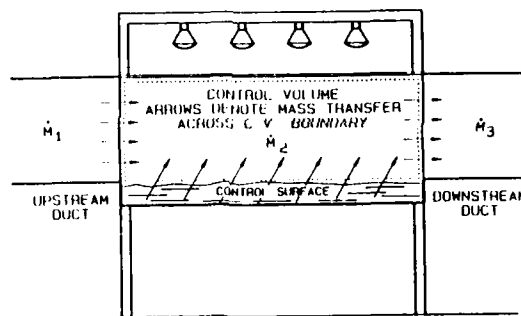

Figure A-1. Revolatilization test control volume.

In revolatilization studies performed in the REAF, m_1 and m_3 are calculated from the concentration of HCl measured upstream and downstream of the test section, respectively. The measurements are made with Geomet HCl detectors.

As a function of concentration, the mass flow is written as

$$m = \frac{C\ V}{t} \tag{A-2}$$

where C is the concentration,

V is the volume, and

t is an increment of time.

The volume V is obtained by the relation

$$V = ASt \qquad\qquad (A-3)$$

where A is the cross sectional area of the chamber duct,

S is the speed of airflow through the chamber duct, and

t is an increment of time.

Substituting equation (A-3) into equation (A-2) and assuming the increments of time are the same leads to

$$m = CAS \qquad\qquad (A-4)$$

which leads to

$$C_1 A_1 S_1 + m_2 = C_3 A_3 S_3. \qquad\qquad (A-5)$$

In the revolatilization run performed on 2 June 1987, the Geomet upstream of the test section (measuring C_1) registered a constant value of 0.0 ppm. This allows the simplification of equation (A-5) to

$$m_2 = C_3 A_3 S_3. \qquad\qquad (A-6)$$

The data gathered by the downstream Geomet (measuring C_3) during the 2 June 1987 run was shown in Figure 19. The average value of C_3 was calculated to be 4 ppm over the one hour run; the air speed was 2 miles per hour.

The cross-sectional area of the chamber duct is 4 ft^2. Using the values of C_3 = 4 ppm HCl and S_3 = 2 mph, m_2 is calculated by

$$m_2 = \left(\frac{4 \text{ moles HCl}}{10^6 \text{ moles air}}\right)\left(\frac{36.5 \text{ g HCl}}{1 \text{ mole HCl}}\right)\left(\frac{1 \text{ mole air}}{22.4 \text{ l air}}\right)$$

$$* (4 \text{ ft}^2)(\frac{2 \text{ mi}}{1 \text{ hour}})(\frac{5280 \text{ ft}}{1 \text{ mi}})(\frac{1 \text{ hr}}{60 \text{ min}})$$

$$* (\frac{30.48 \text{ cm}}{1 \text{ ft}})^3(\frac{1 \text{ ml}}{1 \text{ cm}^3})(\frac{1 \text{ l}}{1000 \text{ ml}}) \tag{A-7}$$

or

$$m_2 = 0.13 \, \frac{\text{g HCl}}{\text{min}}. \tag{A-8}$$

The value of m_2 is converted to a mass flux by the relation

$$o_m = \frac{m_2}{A_2} \tag{A-9}$$

and for the pre-firing run was found to be

$$o_m = (\frac{0.13 \, \frac{\text{g HCl}}{\text{min}}}{(2 \text{ ft})(9.5 \text{ ft})})(\frac{10.76 \text{ ft}^2}{1 \text{ m}^2}) \tag{A-10}$$

or

$$o_m = 0.074 \, \frac{\text{g HCl}}{(\text{min})(\text{m}^2)} \tag{A-11}$$

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